Neutrinoless Double-Electron Capture in ^{36}Ar

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One controversial topic in particle physics is the mechanism by which neutrinos have their recently discovered mass. One possibility is that they are Majorana neutrinos; this would violate the Standard Model, but if this is the case then one possible way of detecting them is through neutrinoless double-electron capture, which can only occur with Majorana neutrinos. Although ^{36}Ar has never been observed to decay, it is capable of undergoing double-electron capture with a half-life greater than 1.85×10^{18} years.[1] In this decay, energy is given off in the form of two neutrinos or, in the neutrinoless case, a bremsstrahlung photon. The Darkside-50 detector at Gran Sasso National Laboratory will be used to look for this photon and if it is not found, a lower limit will be placed on the half-life of the ^{36}Ar nucleus.

Mechanics of Double-Electron Capture

The inverse process to double-beta decay is double-electron capture. In this process, a nucleus absorbs two electrons and two nuclear protons are converted into neutrons, emitting two neutrinos. The energy of the decay is shared between the two neutrinos and a photon of x-ray energy,[1]

$$(A,Z)+e+e\rightarrow(A,Z-2)+2\upsilon+Q. \quad (1)$$

One candidate for this decay is the ^{36}Ar nucleus. As shown in Figure 1, this is an energetically favorable process as the high energy of the ground state of $^{36}_{17}$Cl prevents ^{36}Ar from undergoing single electron capture. Although there are isotopes which can undergo both single- and double-electron capture, there are some (such as ^{36}Ar) which only naturally undergo the latter. It is worth noting that due to the conservation of angular momentum, both electrons cannot be captured from the K-shell.

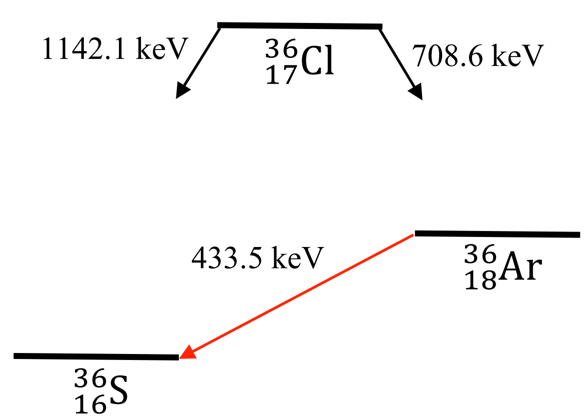

FIG. 1. The double-electron capture of $^{36}_{18}$Ar is an energetically allowed state.[2]

Neutrinos as Majorana Particles

In light of recent discoveries of the mass of the neutrino, it is useful to investigate the mechanism responsible for this mass. One explanation is that neutrinos are Majorana particles, implying that the neutrino is identical to its charge conjugate.[1] This would violate lepton number conservation, and therefore could not happen according to the Standard Model. If the neutrino is identical to its charge conjugate, it is possible that one of the left-handed neutrinos emitted during the double-electron capture process will have the necessary right-handed component to ensure absorption into another nucleon,[1]

$$(A, Z) + 2e^{-} \rightarrow (A, Z-2) + \gamma. \qquad (2)$$

In order to satisfy energy-momentum conservation, in the absence of neutrino emission, the double-electron capture decay energy must be released in the form of a monoenergetic bremsstrahlung photon of energy 430.8 keV.[2] The Q value for the ^{36}Ar double-electron capture process is 433.5 keV. With no neutrinos in the final state, this energy is shared among the X-ray emitted from the electron capture and the bremsstrahlung photon, thereby fixing the bremsstrahlung photon energy at 430.8 keV.

Experimental Setup

The Darkside-50 dark matter detector[3] is a dual-phase TPC using 50 kg of liquid argon as its target. Its primary purpose is to search for collisions of WIMPs with argon nuclei. However, since it is effectively a very sensitive radiation detector, it is possible for us to search for the 430.8 keV gamma from 0ν2EC decay of the Ar^{36} naturally abundant in Darkside-50 WIMP target. Darkside-50 exploits the very powerful scintillation light of liquid argon produced when energy is deposited in the argon. This primary scintillation light is called the S1 signal. The scintillation light is detected by two arrays of photomultiplier tubes (PMTs), one on the top and bottom of the chamber, each array consisting of 19 PMTs. Argon is used because it is relatively inexpensive, dense, and is easily purified as many of the impurities can be removed at very low temperatures. The PMTs are not sensitive to the 128-nm argon scintillation light, and therefore the inner surfaces of the time-projection chamber are coated with tetra-phenylbutadiene, which shifts the wavelength of the scintillation light to a range visible by the PMTs.

Additionally, the top and bottom surfaces of the TPC are coated with indium tin oxide so that they act as the grounded anode and -60 kV cathode respectively. When the hypothetical WIMP interacts with the argon, the atom is ionized, which results in a free electron. A constant electric field of 200 V/cm is applied to the entire volume of the liquid argon, which causes any free electron that did not recombine to produce the S1 scintillation light to rise to the top of the liquid in the chamber. Once the electrons reach the gas phase, they are extracted by a 3 kV/cm electric field. Here they emit more scintillation photons resulting in another signal, $S2$, via electroluminescence.[3]

A diagram detailing the process inside the detector is seen in Figure 1. Although the primary purpose of the Darkside-50 detector is to detect WIMPs, the setup is the same for detecting the bremsstrahlung photon emitted during the $0\nu 2EC$ process of ^{36}Ar. The emitted photon is seen by the PMTs as an S1 signal.

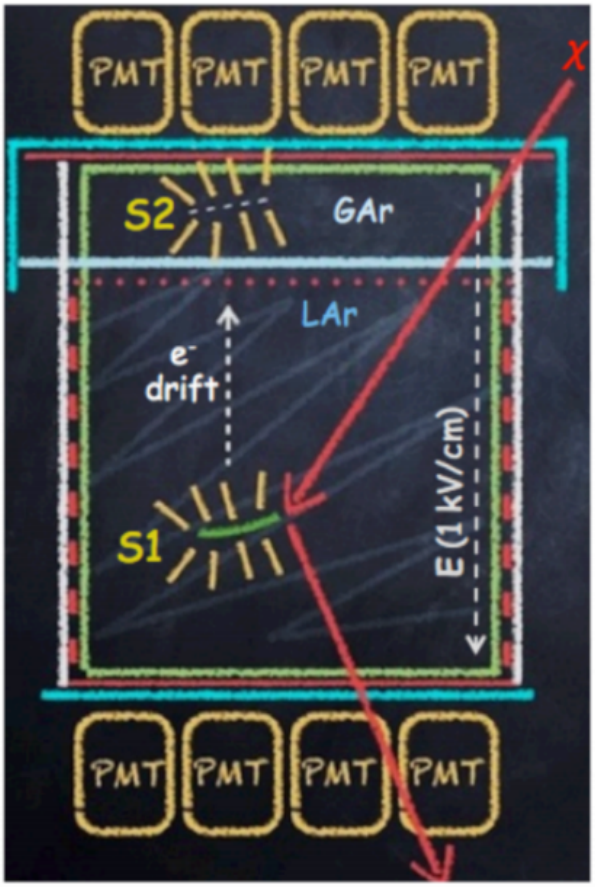

FIG. 2. A WIMP interacts with an argon nucleus emitting a signal S1. The free electrons then drift upwards in the electric field and in the gas emit a second signal, S2.

Purification of ^{40}Ar

One of the most significant challenges to this experimental setup is the necessity of having non-radioactive argon in the detector. Attempts to use atmospheric argon have been made, however the presence of ^{39}Ar (at approximately one part in 10^{15}) causes a significant amount of background radiation. Argon extracted from the Earth's crust, which has been shielded from cosmic radiation for millennia is used instead. The activity of atmospheric argon is ~1 Bq/kg, and this can be reduced by a factor of over 150 by using argon from an underground source.[4] In the extraction well in Cortez, Colorado, the underground gas is collected using a vacuum pressure swing adsorption (VPSA) system. After the gas passes through the system, it is composed of argon at about 3-5%. After being sent to Fermilab for distillation, the underground gas (which consists mainly of helium at this point) is inserted into a condenser booster, a pressurized tube surrounded by a liquid nitrogen jacket, which is used to control the pressure (and therefore the temperature) of the condenser booster. Helium condenses at a very low temperature (~4K) whereas the other gasses (mainly argon and nitrogen) condense at ~87K and ~77K respectively. The temperature in the booster is carefully monitored so that the argon and nitrogen mixture is just above the freezing points in order to minimize their vapor pressure while they, among other contaminants, condense at the bottom of the booster. Due to the vapor pressure of the condensed liquid, some argon and nitrogen still remain in gaseous form, so the gas in the booster is passed through charcoal traps. These traps are stainless steel cylinders filled with extruded coconut charcoal, which adsorbs the gaseous argon (but not helium) when at cold temperatures. The helium is then vented into the atmosphere and when the charcoal is fully saturated, it is warmed up and the argon gas is flowed back into the booster.

When the argon and the other liquefied contaminants comprise most of the volume of the booster, the liquids are transferred to buffer racks to await the next step in purification, distillation. In this step, the gas is passed through cold traps that are designed to freeze out contaminants such as carbon dioxide; the gases then enter the cryogenic distillation column.[5] At this point, the gas is primarily argon and nitrogen. The column consists of a crycooler at the top. The temperature is balanced by a heater on the top and a reboiler on the bottom. The low-radioactivity argon collects in the bottom near the reboiler while the other gasses (primarily N_2) are expelled from the top and vented into the atmosphere. With this distillation procedure, 26 000 standard liters of underground gas is processed each day.

Detecting the 0υ2EC Decay

As shown in Figure 3, the emitted S1 signal due to the beta decay of ^{39}Ar is responsible for most of the signal recorded, making it difficult to discern WIMP or ^{36}Ar electron capture interactions from that of typical ^{39}Ar decay. The ratio of ^{39}Ar to ^{40}Ar in atmospheric argon is 8.6×10^{-16}, and the resulting activity level is 1 Bq/kg.

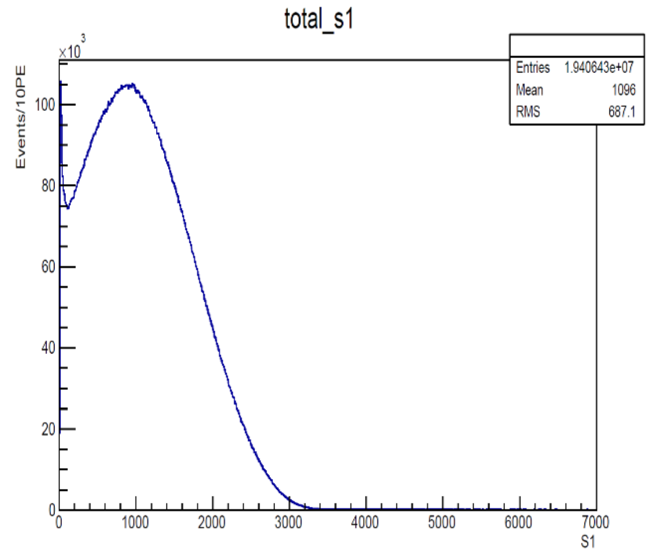

FIG. 3. 1.94×10^{7} *events were recorded and a histogram of their emitted photoelectrons (S1) was taken. The bin width is ten photoelectrons. The vast majority of the data is due to the radioactive decay of* ^{39}*Ar.*

All of the events recorded in the histogram were recorded in the presence of a non-zero electric field, which presents a major challenge. In order to be as accurate as possible, both S1 and S2 must be considered. For the sake of simplicity in these early calculations, only S1 was read in. This results in significant inaccuracy when looking for the monoenergetic photon emitted during the double-electron capture of ^{36}Ar. To increase the accuracy while only considering the first signal, S1, it is necessary to only take data from null field runs, meaning where the electric field in the liquid argon is zero. This results in the free electron not being extracted, so the S2 signal is definitely zero. The number of null field runs that have been run on Darkside since its commissioning are minimal (~50), so the future plans for this project are two-fold. The first priority is to request more null field runs on the Darkside-50 detector, and the next is to begin data analysis of S1 and S2 simultaneously.

Limiting the Half-Life of ^{36}Ar

In the absence of this monoenergetic photon, which would confirm the existence of the neutrinoless double-electron capture of the ^{36}Ar nucleus, the run time for the duration of which the photon was not found can be used to place a lower limit on the half-life of the nucleus. The natural abundance of ^{36}Ar in atmospheric argon is 0.336%, so 50 kg of argon consists of 168 g, or 4.67 mol of ^{36}Ar; this translates to 2.81×10^{24} atoms. With an initial number of atoms A_0 and an "observed" quantity $A = A_0 - 1$ (the worst case scenario is assumed, that the nucleus decays immediately before and immediately after observation) after a period of time t, the half-life h can be expressed as

$$h = \frac{0.693t}{\ln\left(\frac{A}{A_0}\right)}. \quad (3)$$

For the null field runs which have been performed with the Darkside detector over the last several months, the total live time was 2.5 hours. With the previously mentioned number of ^{36}Ar atoms and assuming no decays will be seen within that live time and that ten decays could be differentiated from the background (a highly optimistic and impossible guess), the half-life h must be at least 6×10^{18} years, in comparison to previous experimental results of 1.85×10^{18} years.[2] These results are strictly hypothetical and are assuming the photon is not found, as an algorithm has not yet been developed to separate the signal of the bremsstrahlung photon from the ^{39}Ar decay background. In addition, ten single beta decays could not be differentiated from the background caused by the ^{39}Ar decays.

Future Plans

This is a fairly new project, so the only results that could be used are those that already existed in the Darkside database. In the future, more null field runs from the Darkside detector will be requested and from the existing runs both the S1 and S2 signals will be analyzed. Although it was thought at first that finding the "live time" to serve as t in eqn. (2) would be trivial, in reality the time elapsed during each run varies significantly, so in the future an algorithm will be developed to calculate the live time for each run. In addition, an algorithm will also be developed to model the ^{39}Ar decay so the bremsstrahlung photon can be found in spite of it. By increasing our ability to analyze the data, we can more accurately search for the monoenergetic photon emitted in the double-electron capture of ^{36}Ar or, in its absence, calculate a lower-limit for the half-life of this isotope.

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